# Nonlinear dynamics of hybrid Josephson junction with an oxide antiferromagnetic interlayer

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***Abstract*— Microwave dynamics of Nb/Au/CaSrCuO/YBaCuO hybrid Josephson junctions were studied under mm wave probe signals. Oscillating with microwave power integer and half-integer Shapiro steps were observed. Moreover at frequency f=45 GHz a "devil" staircase structure was registered within two narrow power ranges of external microwave signal. At f=70 GHz "devil" steps disappeared and half-integer Shapiro steps became much smaller than at f=45 GHz, but a giant noise-like signal was registered using cooled 1-2 GHz band HEMT preamplifier at biasing voltages corresponding to the half-integer Shapiro steps.**

## I. INTRODUCTION

AT the interfaces between superconducting and magnetic materials the interplay between superconducting and magnetic ordering results in novel physical phenomena giving opportunities for promising applications in electronics. For instance, in ferromagnetic/superconducting/ferromagnetic (F/S/F) structures the superconductivity can be controlled by spin manipulation in F electrodes [1]. Another effect is the oscillatory behavior of the superconducting order parameter induced in the ferromagnetic layer that may lead to π-phase shift in the ground state of S/F/S Josephson junction. Interesting effects occur also at superconducting and antiferromagnetic (AF) S/AF interfaces. Recently multilayer hybrid Josephson junctions Nb/Au/$Ca_{1-x}Sr_xCuO_2$/$YBa_2Cu_3O_{7-\delta}$ with S/AF interface have been fabricated [2], where $YBa_2Cu_3O_{7-\delta}$ (YBCO) is oxide *d*-wave superconductor, Au - normal metal, and $Ca_{1-x}Sr_xCuO_2$ (CSCO)– AF layer. It's known [3] that Josephson junctions driven far from equilibrium at microwave frequencies may demonstrate noticeable deviations of high frequency dynamical characteristics predicted by resistively shunted (RSJ) model. In this connection a set of measurements of I-V characteristics under irradiation of electromagnetic field, along with the dc controlled applied H-field has been carried out.

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## II. SAMPLES AND MEASUREMENTS

The CSCO/YBCO epitaxial double-layer was grown in situ by pulsed laser deposition on $NdGaO_3$ substrates. In order to avoid micro-shorts the following precautions have been made: (i) CSCO films ($d$=20 ÷ 50 nm) were thicker than the RMS surface roughness of the YBCO layer; (ii) Nb/Au bilayer serves as superconducting counter-electrode. Note, if Nb deposited directly on the top of YBCO film it results in formation of Nb/YBCO interface with very high resistance (~1 $\Omega\times cm^2$) due to Nb surface oxidation. For measurements the experimental variables were microwave frequency f=45 GHz or 70 GHz with power controlled by the precision attenuators in the range of α=0÷70 dB. Power of background noise of the junctions was measured within frequency band 1-2 GHz by the two-stage amplification with low noise cooled HEMT preamplifier and simultaneously controlled by spectrum analyser. For impedance matching of junctions with the HEMT amplifier measurements were done over 2-point connection, resulted in dc series resistance of order of few mΩ. Pulse-free electronic apparatus and the battery dc power supply were used for I-V curve measurements. Magnetic field was applied using analogue dc supply. All measurements were carried out at T-4.2 K in magnetically shielded cryostat in microwave-screened room.

## III. RESULTS AND DISCUSSION

Most of experimental samples had symmetric RSJ-type I-V curve without excess current and the product of critical current by normal resistance $I_OR_N$ ~ 200 μV at T=4.2 K. Estimated values of McCumber parameter obtained from ratio of forward and return critical current gave $\beta_C$=1÷3. Oscillating with microwaves power amplitudes of integer Shapiro steps demonstrated good fit to RSJ model. At the same time, half-integer Shapiro steps were registered. Superposition of magnetic and microwave fields did not lead to distortion in symmetry of I-V curves and equal heights of Shapiro steps at positive and negative current bias were observed. All junctions were "short" with dimensions less than Josephson penetration depth. Under microwave irradiation at 45 GHz a "devil" staircase structure was observed. Note, such behavior was not observed for samples discussed earlier [4]. Fig.1 shows evolution of I-V curves under microwaves when applied power was changed. Distortion of the $2^{nd}$ Shapiro step is seen at large power levels (Fig.1b ) within narrow attenuation range α=3 dB.

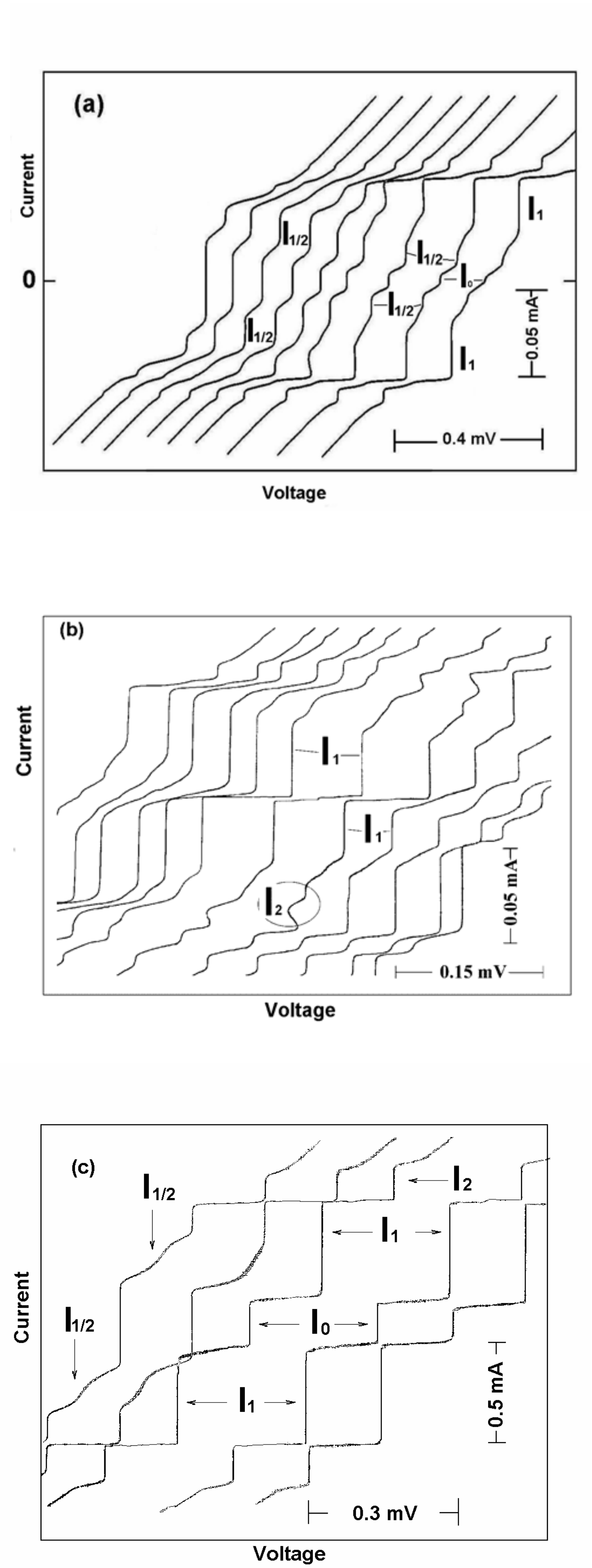


Fig. 1. Families of I-V curves under microwave irradiation f=45 GHz (a, b) and f=70 GHz (c). Critical current $I_0$, integer $I_1$, $I_2$ and half-integer $I_{1/2}$ Shapiro steps are indicated. (b): n=2 Shapiro step distortion is pointed by circle. (c). chaotic noise rise corresponds to the jerks on $I_{1/2}$ steps. All curves are shifted by voltage to the right with increase of applied power. AF interlayer was $Ca_{0.5}Sr_{0.5}CuO_2$, dimensions 20x20 μm, *d*=20 nm, $I_0$=55 μA, $R_N$=5.5 Ω, and $\beta_C$=2.

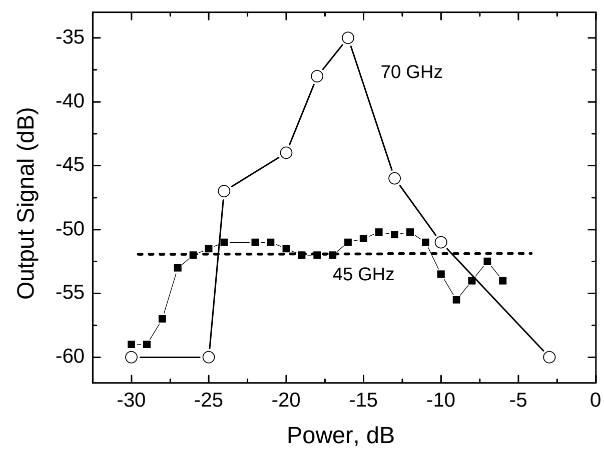


Fig. 2. Output signal measured in 1-2 GHz frequency band under microwave power P at 45 GHz (black symbols) and 70 GHz (open symbols). Dash line shows saturation level for frequency mixing.

Fig.1a demonstrates unusually large half-integer n=1/2 Shapiro steps: up to 0.4 of critical current $I_0$. That could be caused by superposition of two processes, first is due to existence of the second harmonic in current-phase relation, and the second one related to the period doubling under the large microwave signal at frequency not far from plasma frequency $f_P=f_C(\beta_C)^{-1/2}$ of Josephson junction, where $f_C=2e/h(I_0R_N)$ is critical frequency. Fig.1c shows I-V curves when giant noise rise was observed at biasing voltages corresponded to the voltage biasing of the half-integer Shapiro step when 70 GHz signal was applied. Affected by external signal a frequency mixing takes place as well. However, applied strong power results in output signal saturation and the excess noise-like output signals could be explained by chaotic oscillations. Fig.2 shows the output signals for the cases of 45 GHz and 70 GHz and the level of the saturation of output mixing product. Experimental conditions for chaotic oscillations in “short” Josephson junctions were analyzed [3] and experimentally observed [5] in the case $\beta_C$ >25. Note again, our junctions had relatively small $\beta_C$ values. Recently chaotic dynamics was predicted [6] for S/F/S Josephson structures with magnetic interlayer consisted of 3 separated F-layers with rotated magnetization. Although we did no obtained experimental evidence for the triplet Josephson effect in our structures, the latter finding point on very complicated high frequency dynamics in Josephson junctions with magnetically active interlayer. Obtained results show that along with a search of better magnetic interlayer material the microwave dynamics must be studied to avoid chaotic behavior and unstable operation of novel Josephson devices with magnetic barriers.

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